COMPARISON OF GAMMA RADIATION EFFECT ON ERBIUM DOPED FIBER AMPLIFIERS

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SUMMARY
Optical amplifiers have many applications in space, such as transmitters, receivers, for satellite telecom, lidars and remote sensing. They are compact, light-weight, and offer high speed data transfer and high wall-plug power conversion efficiency. Their importance is increasing with their potential use in the new large constellation projects proposing hundreds of satellites, planned by different international consortiums for 2018-2025. The optimal amplifiers candidates, the Erbium and Erbium Ytterbium Doped fiber amplifiers (EDFA, EYDFA) have a major limiting factor, their relative sensitivity to gamma radiations. Recently a few companies started proposing radiation hardened (radhard) EDF and EYDF, and in parallel many commercial products improved their resistance to radiation. A set of radhard and commercial fibers from various suppliers were submitted to gamma radiation tests (total 100 krad), including, EDF, EDF Polarization Maintaining (EDF -PM), EYDF) and EYDF-PM. In total five tests have been performed, with different dose rates in three laboratories; two tests were using a Sc46 source of gamma ray, and three test with Co60. A summary of the results is presented and analyzed. As an example of EDF in real space environment, the evolution of the intensity of three fiber sensors on Proba2 mission are presented (7 krad total dose in almost 7 years). They are parts of the Fiber Sensor Demonstrator (FSD) payload. The three fiber sensors are in different locations on Proba2 satellite (thruster, propulsion tank, pressurized fuel tank), at the end of line after EDF amplifiers and Fabry Perrot Filters.

I. INTRODUCTION

I-A. International and Commercial Interest

Optical space telecom has been developed since SILEX and Galileo projects in the early 1990s [1]. The first Optical Inter-Satellite Link (OISL) between SILEX and Artemis was demonstrated in 2001[2]. Evolving internet market has re-launched in 2014 the interest in optical satellite telecom, following the plan of Google and Facebook to invest in the development of large constellations using optical telecom. There are tremendous potential commercial applications in particular to connect a considerable percent of the Earth population to the Internet. Examples of the current international projects are:

- Google: 300-500 satellites at Low Earth Orbit (LEO) at about 700 km, sending the optical signal to large balloons called High Altitude Platform (HAP) at about 15-20 km, then the signal is sent to Ground either optical or RF form.
- Facebook: 300-500 satellites at LEO at 700 km sending the optical signal to drones at 12 km; then the signal is sent to Ground either optical or RF form.
- Airbus/Oneweb/ SpaceX: 700 small satellites at LEO with direct RF signal to ground. They consider connecting satellites at GEO (36700 km) to LEO by optical signal.
- Optus/Laser-light with the first Optical Satellite Service provider about 12 MEO satellites, proposing an all-optical, laser-based terrestrial/satellite network.
- Inmarsat – RUAG: 350-450 satellites Public-Private-Partner (PPP) with ESA
- Thales Alenia Space: 90-110 satellites at LEO with two options of optical signal either to Drone or to Ground directly
- Various projects for large drones or HAP in stratospheres (Astrium/, Zephyr and TAS/Stratobus)

I-B. MPB Experience with Optical amplifiers

MPB has started its projects in optical telecom for space within a contract for ESA reviewing the feasibility of fiber laser for OISL in the mid-1990s. There were many technical obstacles to solve. The following contracts with ESA in the early 2000s were to build EDF amplifiers at lower power levels for intra-satellite applications and as a source of lasers for fiber sensor Interrogation. The technology has greatly improved with optical fiber amplifiers at 20 W output in the 1550 nm range being built for terrestrial application. Recently MPB built the amplifier stages of the four very high power laser guide star (4x22W, 589 nm) within an ESO contract, and successfully tested them in April 2016 [3].

Table-1 summarizes the heritage and roadmap of EDFAs for space at MPB, with the amplifier output power and the TRL.

Table 1: Summary Space Qualification Tests of MPB's EDFAs

EDFA qualified	Output (dBm) /1 dBm Input	Year of qualification	TRL Now	TRL End of Mission
- EDF Tunable laser for Interrogation of the Fiber Sensor Demonstrator, 4 lines x6 fiber sensors each, - System flying on Proba2 ESA's satellite since Nov. 2009 - Built for 2 years mission, completely functional after 7 years	13	2005	7	8
6 EDFAs tested by Alter-Technologica and TAS for ESA including radiation test Completed in 2008	15	2007	5-6	5-6
EDFA light source 15 dB gain, for Fiber sensor on Atmospheric Reentry mission (ESA-DLR)	17	2014	6	6 (2016)
Medium Level Optical Amplifier (20 dB gain) for ESA-/Thales-Alenia Space 4 amplifiers in compact box	20 -21	2013-2016	4	5-6
On-going contract with ESA: Medium power (15-24 dBm) and Low Noise amplifiers (Gain > 44dB at -7 dBm input)	15-24	2014-2016	4	5-6
On-going contract with ESA : High power PM amplifier (LEO satellite to ground, Drones or High Altitude Platform)	>40	2015-2017	3-4	5-6

II. EXPERIMENTAL SET UP

II-A. Description and general parameters

Five separate tests were performed under several conditions. Two tests used the Sc-46 and Three the Co-60 (Table2 and Table3). Some EDFs and EYDFs were pumped, in forward or backward configuration, to obtain similar output as their final use as amplifiers. The power output level in these active configurations was between 18 dBm (medium power) and 33 dBm (High power EYDFs). Other fibers were kept in passive form not pumped during irradiation to simulate the redundant amplifier. One fiber the EDF1-MPB used in MPB commercial EDF products was a witness for all the five tests and all configurations.
Table-2 compares the parameters of the five tests and the number of fibers irradiated in each of them, and Table-3 compares the radioactive characteristics of the Sc-46 and Co-60

The objectives were to test:

- Different gamma radiation sources, the commonly used Co-60 and a the Sc-46 that has slightly lower gamma energy (Table 3)
- Use different laboratories to avoid hidden potential systematic error.
- For the same total dose of 100 krad, use different radiation dose rates, some are close (220, 240 and 360 rad/h, and lower dose such as 100 rad/h. The short half life of the Sc-46, permitted a dose of 20-50 rad/h.

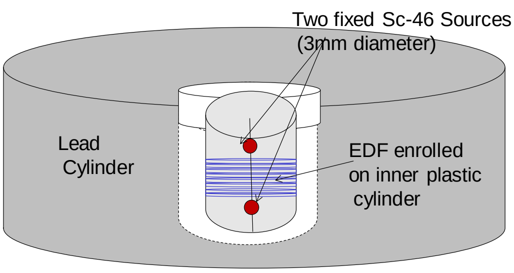
Fig. 1 and Fig. 2 presents illustrate the irradiated fibers set up at Ecole Polytechnique and at ESTEC

Table 2: Comparison of the test parameters between the five tests performed

Parameter	Polytec-1	Polytec-2	ESTEC-1	ESTEC-2	Alter-Tech.
Location	Montreal, Can.	Montreal, Can.	Noordwijk, Neth.	Noordwijk, Neth.	Sevilla, Spain
Radiation source	Sc-46	Sc-46	Co-60	Co-60	Co-60
Date	January 2013	July- Nov. 2013	May-June 2014	Nov.-Dec. 2015	August 2016 (to be analyzed)
Test Duration (Days)	20	129	12	43	23
Dose Rate (rad/h)	235	Deb:52 / Fin:18	363	108	215
Total Dose (Krad)	101.5	125.2	106.7	110.3	101
Total Dose (Gy)	1015	1252	1067	1103	1010
Total number of Fibers	4	3	22	25	15
Standard EDF tested	Yes	Yes	Yes	Yes	Yes
PM-EDF tested	No	No	Yes	Yes (more)	Radhard
EYDF tested	No	No	Yes	Yes (less)	No
PM-EYDF tested	No	No	No	Yes	Yes

Table 3: Comparison of the test parameters between ESTEC1 and ESTEC2

Parameter	Sc-46	Co-60
Physical-Half-life (days)	83.83 days	1925.20
Maximum Beta Energy: (MeV)	0.357 (100%)	0.665 (100%)
Gammas (MeV)	1.121 (100%)	1.33 (100%)
	0.889 (100%)	1.17 (100%)
Maximum Range of Beta in Air (cm)	84	125
Half-Value Layer (HVL) for Lead Shielding (mm Pb)[4]	12.5	15.6
Exposure Rate (C: m^2/kg.MBq.s) Coulomb per kg per second for a given activity in MegaBecquerel at a distance in meters[4]	$2.09\ 10^{-12}$	$2.50\ 10^{-12}$
Exposure rate (R: cm^2/m.Ci.h) Roentgens per hour for a given activity in milliCuries at a distance in centimeters [4]	10.8	12.9
F-factor (cGy/R) [4]	0.965	0.965



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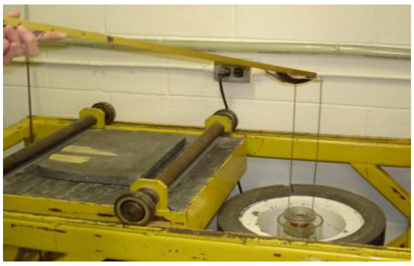
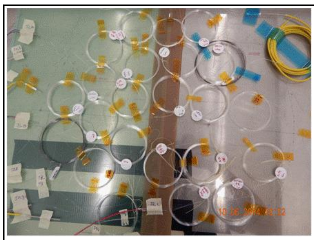


b)

Figure 1: set up at Ecole Polytechnique Montreal using Sc-46- a) schematic and b) picture

The source is formed of two small pellet separated by 3 cm distance to permit a uniform distribution over 4.5 cm height within ± 2%. The fibers are enrolled on a thin plexi-glass spool. A perch and two rods permitted to hold and monitor the spool



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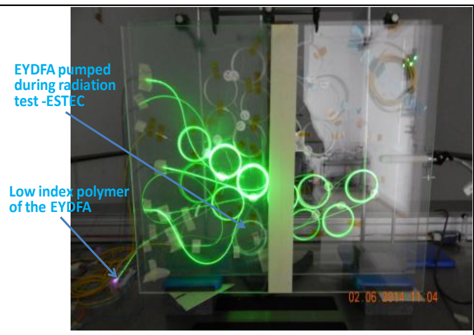

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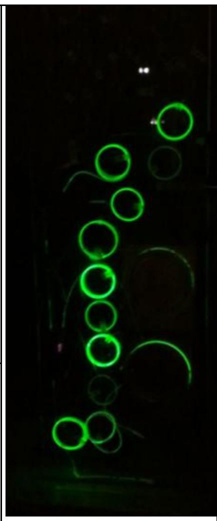

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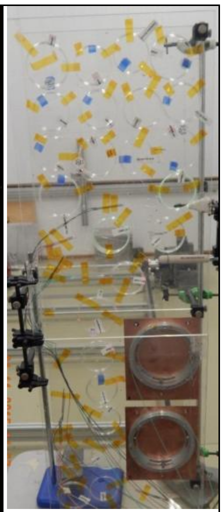

d)

Fig.2: Pictures of the fibers under irradiation
a) ESTEC-1 on the panel (light On)
b) ESTEC-1, illuminating pumped fibers with the light off,
c) ESTEC-2, illuminating pumped fibers with the light off
d) ESTEC-2 on the panel (light On).
We can see in b) the low index shining polymer makes the interface between the Single mode passive fiber and the double cladding EYDF.

III. EXPERIMENTAL RESULTS

The gain and the Noise Figure spectra of each doped fiber were measured before and after each complete test, using an Optical Spectrum Analyzer. A laser diode provided the total power between 1500 and 1580 nm before and after the test, a global parameter, used to confirm the detailed spectra measurements. The results of gamma radiation effects are presented and the response of the several fibers are compared.

III-A. Polytech-1 and Polytech-2 Measurements

The tests with the Sc46 permit the use of only small number of fibers. Four fibers were used, one MPB commercial fiber in passive mode (EDF1-MPB, medium doping Er) and three radhard fibers in active mode (AMP1, AMP2 from Ixfiber and Elite-TM from Draka). The characteristics of the radhard fibers are given in Table4, and the measurement results are shown in Fig.3, Fig.4, Fig.5 and Fig. 6.

Table 4: Radhard Fibers Characteristics

Fiber Name	IXF-RAD-AMP-1	IXF-RAD-AMP-2	DrakaEliteTM eNanoElite-RH-3
Fiber Type	Er Medium doping	Er High doping	Er Low doping
Absorption @ 980 nm (dB/m)	7 - 9	12 - 15	-
Peak absorption coefficient @1530 nm (dB/m)	12 - 16	22 - 28	3
Mode Field Diameter MFD @1550 nm (µm)	5.5 ± 1	5.5 ± 1	4.2± 0.7
Background losses (dB/km)	< 15	< 20	< 5
Cutoff wavelength (nm)	< 1150	< 1150	1150
Splice loss (dB)	< 0.2 (SMF28)	< 0.2 (SMF28)	_
Radiation Induced Attenuation (RIA) dB/krad	< 0.07	< 0.05	0.05
Mode Field Diameter MFD @1550 nm (µm)	5.5 ± 1	5.5 ± 1	4.2± 0.7

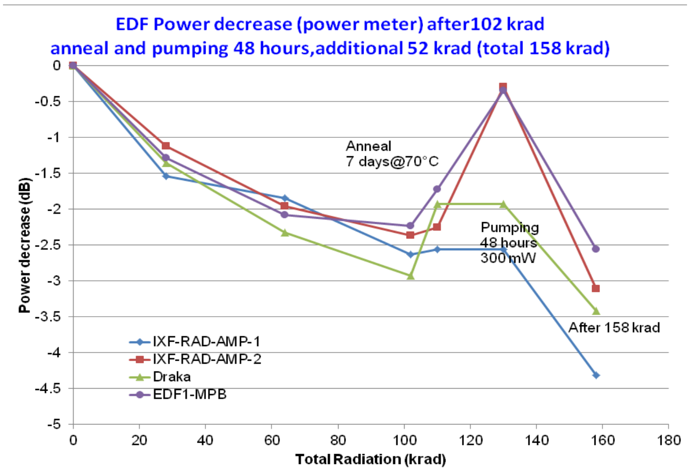

Fig. 3: Polytech-1 Total optical power evolution of the four fibers during the radiation from 0 to 102 krad, followed by an annealing of one week at 70°C, then 48 hours pumping (300 mW at 976 nm) and additional 56 Krad up to 158 krad.

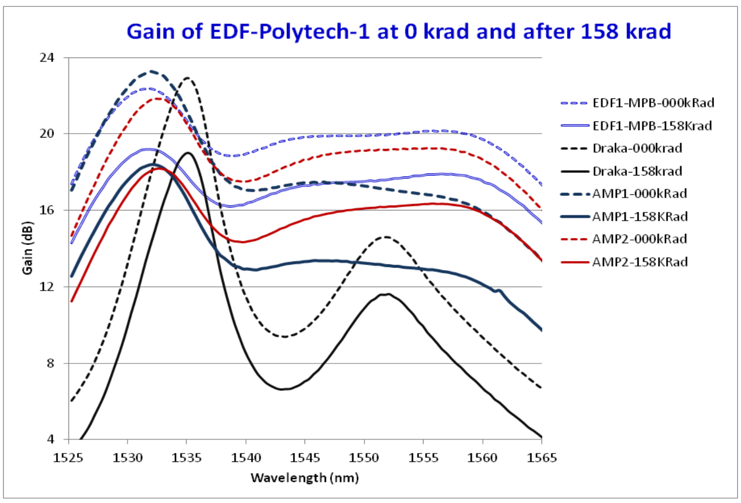

Fig. 4: Polytech-1 Gain spectra before (dashed lines) and after 158 krad the shape is kept

All of the four fibers have similar losses at 100 Krad. During each measurement (25 and 60, 102 and 158 Krad), we waited about 90 minutes, with pumping to stabilize the gain. During this time the gain was increasing very probably with the effect of photo-bleaching. We note that the Gain spectra shape stayed practically the same for each fiber. The loss of the commercial fiber was about the same of that by the rad-hard.
In the test Polytech2 we used the AMP3 from Ixfiber in active forward pumping configuration, and the commercial fiber EDF1-MPB in three different configurations, passive, active forward and active backward configurations.

The AMP3 showed the best performance, the EDF1 backward pumping was less affected by the radiation. The EDF1 in passive configuration had about 1.5 dB more losses than those in active. In Polytech-2 the Sc-46 became to be relatively weak, the dose rate started at 52 rad/h and at the end of the test was about 19 rad/h with 129 days of irradiation. The major disadvantage of the backward pumping is the relative high Noise Figure as shown in Fig.6. The Noise Figure of the AMP3 is slightly higher than the EDF1, in similar configuration. The Noise Figure slightly increases with the radiation 0.2 to 0.5 dB

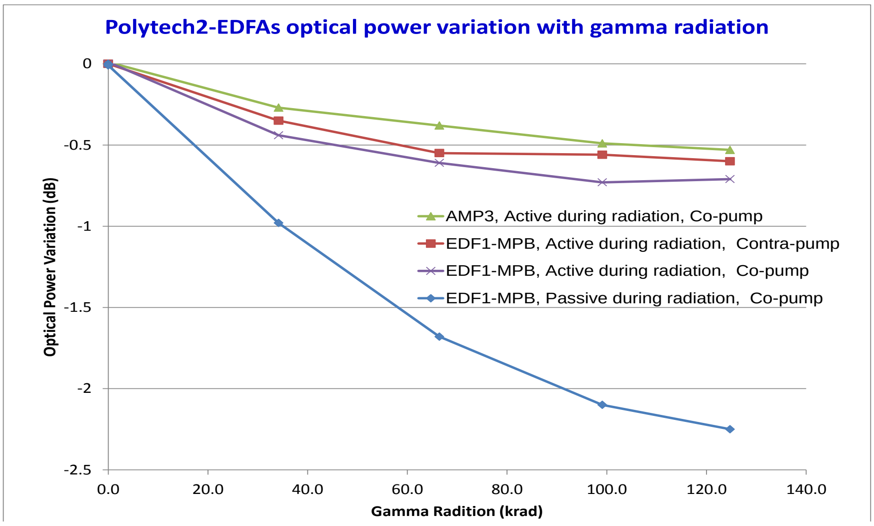

Fig. 5: Polytech-2 Gain Losses fromthe totalpower measurements

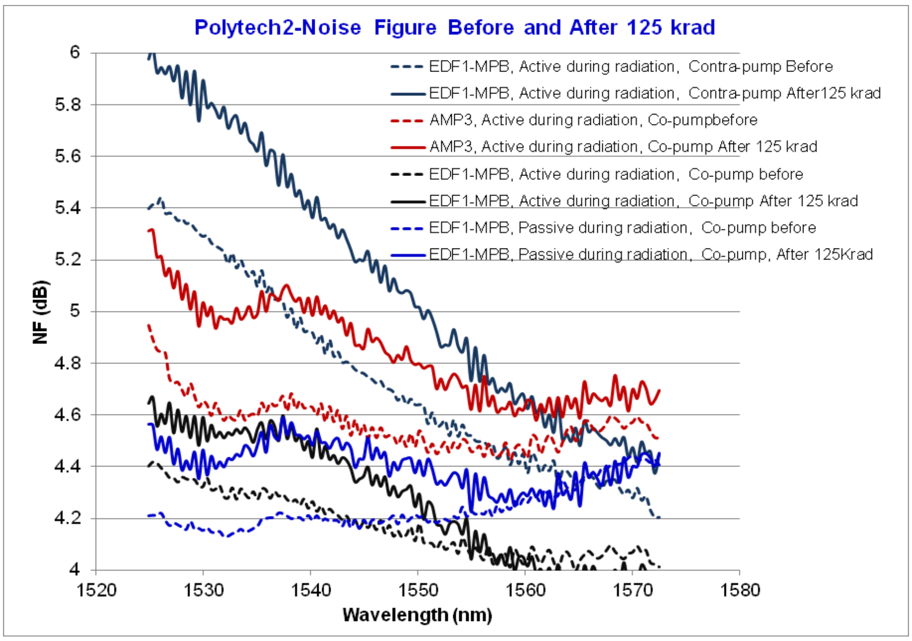

Fig. 6: Polytech-2 Noise Figure before (dashed lines) and after 125 krad

III-B. ESTEC-1 and ESTEC-2 Measurements

In these tests many more fibers could be tested at the same time, and the results are presented.

Fig.7 compares the gain loss of the EDF1-MPB in ESTEC-1and ESTEC-2 considering all the configurations. Fig.8 shows the spectra of an EDF-PM pumped at 650 mW during the irradiation then after the irradiation. The Gain loss is high about 4-5 dB, however the gain could be increased with additional pumping during 5 days. The EDF-PM in passive configurations lost more than 8 dB during the irradiation. The EYDF are backward pumped, they show much less gain loss< 2.5 dB in all cases, about 0.5 dB for the radhard ones (see Table5)

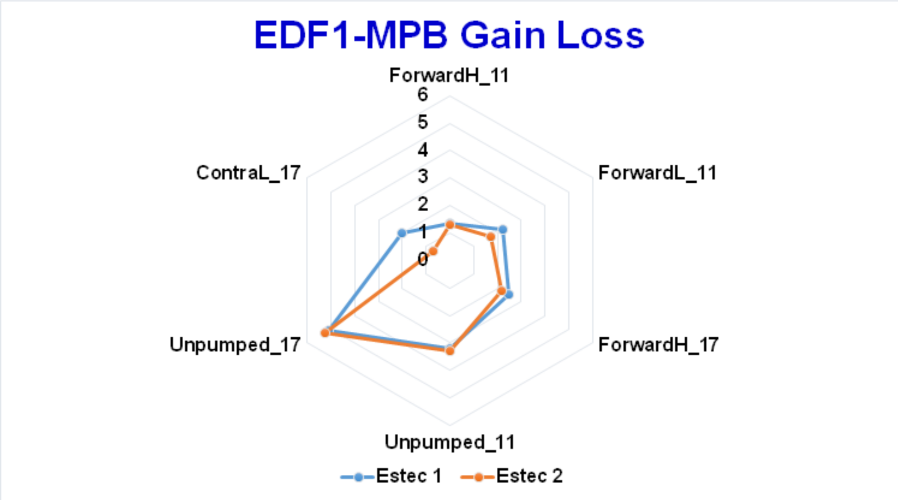

Fig. 7: Comparison of EDF1-MPB Gain Loss between ESTEC-1 and ESTEC-2

- Unpumped_17: 17 m EDF1 not pumped during the irradiation, measured with at 750 mW before/after test
- Unpumped_11: 11 m EDF1 not pumped during the irradiation, measured with at 300 mW before/after test
- ContraL_17: 17 m EDF1 pumped during the irradiation at 300 mW, in backward configuration, measured with at 300 mW before/after test.
- ForwardH_17: 17 m EDF1 pumped during the irradiation at 750 mW, in forward configuration, measured with at 750 mW before/after test
- ForwardH_11: 11 m EDF1 pumped during the irradiation at 750 mW, in forward configuration, measured with at 750 mW before/after test
- ForwardL_11: 11 m EDF1 pumped during the irradiation at 300 mW, in forward configuration, measured with at 300 mW before/after test

Note that the gain loss is probably slightly smaller in ESTEC-2 test with the dose 110 rad/h compared with ESTEC-1 at 363 rad/h

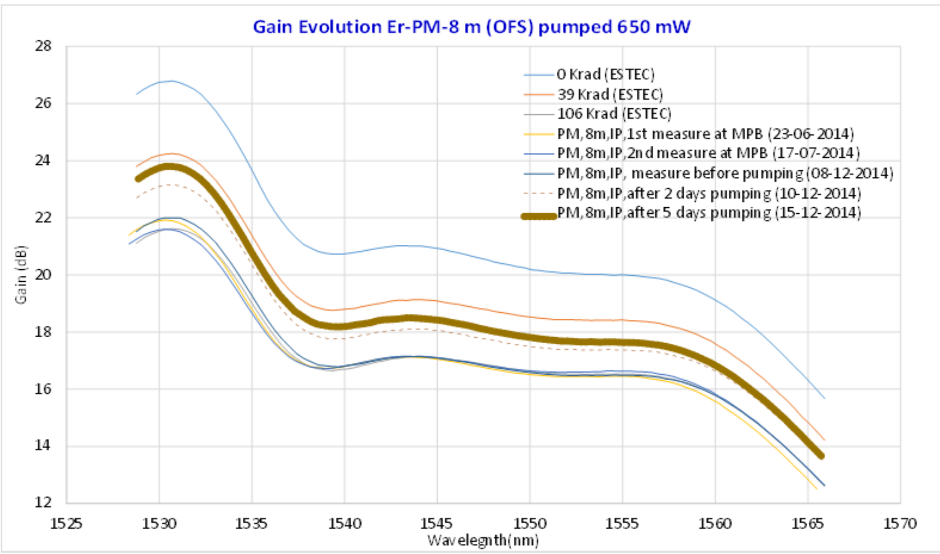

Fig. 8: Evolution of EDF-PM from OFS, Irradiated, pumped during irradiation at 650 mW

Table 5: Summary of the EYDF radiation tests

EYDF Fiber #	Company	Species	State during RadTest	Output Power Ref. (0 krad) (dBm)	Output Power After 106 krad (dBm)	Reduction After 106 krad (dB)
1	A	Standard	Unpumped	28.8	26.7	2.1
2	A	Standard	Pumped	28.8	27.5	1.3
3	B	Radhard-1 (> 100 krad)	Unpumped	27.05	26.55	0.5
4	B	Radhard-1(> 100 krad)	Pumped	27.05	26.8	0.2-0.3
5	C	Radhard-2 up to 20 krad	Unpumped	28.5	27	1.5
6	C	Radhard-2 up to 20 krad	Pumped	28.4	27.9	0.5

III-C. Proba2- Fiber Sensor Demonstrator Measurements

The EDF are being tested in a LEO environment. They are part of the Interrogation module which monitors the Fiber Bragg Grating sensors of the "Fiber Sensor Demonstrator" (FSD) payload on Proba2 satellite. They are in orbit since November 2009.

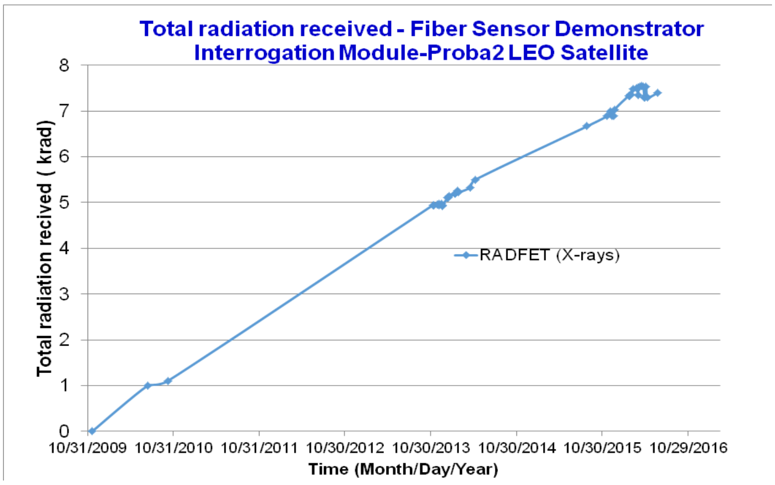

Fig. 9: Total Radiation received in the FSD- during the 7 years flight.

The radiation received inside the Interrogation module is about 1 krad /year. The fluctuations are due to the temperature variations between the measurements as shown in Fig.10

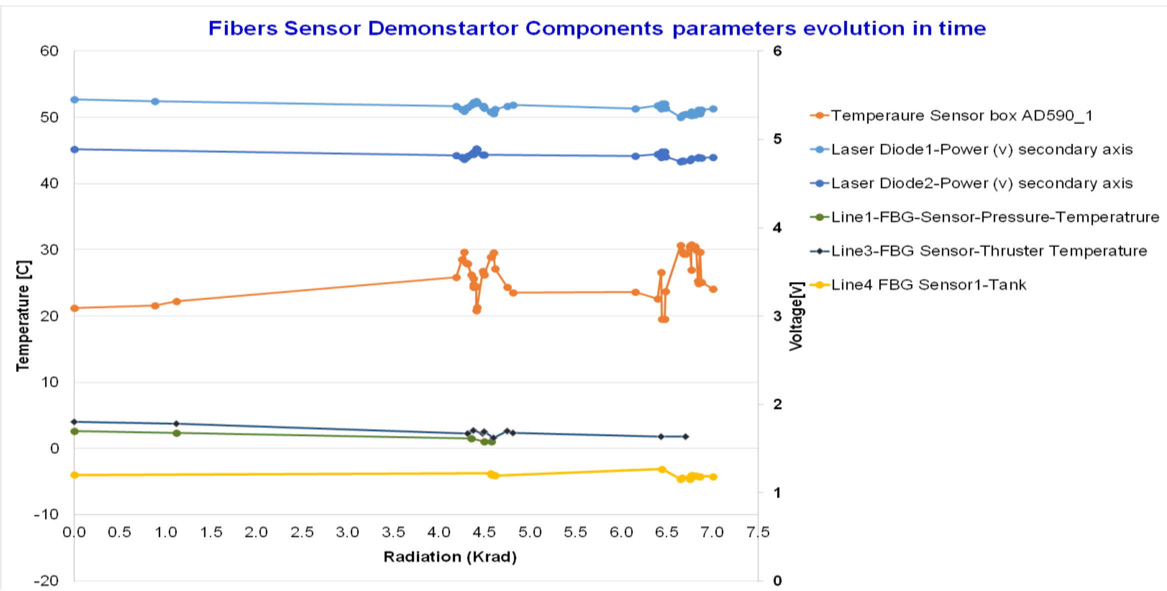

Fig. 10: Evolution of different components as function of the radiation from the Fig.9

There is less than 2 % reduction in the laser diode pump measurements –they are sensitive to temperature that is fluctuating between 18°C and 32°C. We compare the maximum intensity of three FBG sensors on three different fiber lines, one on the pressurized fuel tank, one on the thruster and one on the propulsion tank. The fiber sensors are at the end of the optical circuit lines after the laser diode pumps, the EDF amplifier, the Fabry Perrot Tuneable Filter and circulator. The FBG sensors show less than 3% decrease in its intensity.

IV. DISCUSSIONS AND CONCLUSION

Several radiation hardening techniques have been suggested to enhance the radiation tolerance of the EDFs and EYDFs (Table 6)where most of them were analyzed by MPB.One EDF fiber in particular showed tolerance to radiation. It is the AMP3 from Ixfiber with less than 0.8 dB loss (100 krad) in all the passive and active configurations.

Some part of the gain lost during irradiation can be recuperated by photo-bleaching effect, i.e. putting the fiber in a functional active mode for a few days after the irradiation test. Many commercial fibers could have an after photo-bleachng loss of less than 3 dB.

Baking the fibers at 70°C for one week did not give a considerable annealing effect.

Additional EDF, EYDF fibers are currently under radiation test at Alter will be analyzed after the test.

Table 6: Summary of EDF and EYDF processing methods to improve their rad-hardness

Processing Method	Comments (These methods were described in ICSOs 2010, 2012 and 2014)
Hydrogen Loading	Ixfiber is using this technique for its radhard AMP3 micro-structured EDF having hydrogen in its channels. MPB demonstrated the feasibility principle by loading the EDF, however it is an issue to keep the right H_2 concentration without diffusing in time.
Adding dopant of resistant materials	Injecting high Z element (Ce) to stabilize the Erbium. Ixfiber is using this technology for their EYDF [5] from whom MPB purchased these fibers.
Implanting atoms or ions in preferred depth	Implanting Hydrogen in EDF core using an accelerator and proton beam. The protons energy is adjusted to deposit them in the EDF core. The implanted protons are more stable than those loaded by pressure. The feasible length is limited to a few cm.
Injecting Nanoparticle (e.g Si)	Increase radiation tolerance by reducing the concentration of Al and P using nano-particle deposition techniques. Draka is using this technology [6]
Annealing by heating	To stabilize the ions and atoms in their position [7]. The fibers tested by MPB did not show an improvement with annealing by heating after radiation.
Irradiation with UV, Visible or IR	Irradiation with UV light did not improve the gain after radiation. However additional pumping at 980 nm showed a slow gain recuperation.
Neutron Irradiation	Fixing atoms and ions in their location, proposed, no experimental data [7]

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